Another Way to Go?
Some Implications of a Light-Duty Diesel Strategy

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ABSTRACT

Conventional wisdom suggests that a large-scale shift from gasoline to diesel light-duty highway vehicles would have an impact on energy consumption, emissions and infrastructure. Under a relatively modest scenario, based upon French experience since 1970, a dieselization strategy could have displaced slightly more than half a quad of petroleum (3.7% of the energy consumed by light-duty vehicles) in 1992, while reducing CO, HC and NO_x emissions by 6.3, 0.8 and 0.09 million tonnes, and increasing SO_x and PM10 by 0.03 and 0.2 million tonnes, respectively. Energy consumed in refining would also have been marginally reduced, although additional processing could have been required to increase the fraction of distillate and decrease that of gasoline. Finally, a shift to diesel could have broad implications on U.S. and world oil markets, modifying crude oil supply-demand balances, and requiring a different mix of unit operations in domestic refineries which, in turn, could change the capital investment path of the industry which is currently geared to maximizing gasoline production.

This analysis used the Integrated Market Penetration and Anticipated Cost of Transportation Technologies (IMPACTT) model and EPA's Mobile5a model. Petroleum displacement resulted from the increased thermal efficiency of diesel engines less that portion of gasoline comprised of non-petroleum-based additives for octane enhancement and/or oxygenation as mandated by law or regulation. Emissions reductions resulted from a combination of lower EPA-test emission factors for current-technology diesel engines, much slower in-use degradation of diesel as compared with gasoline vehicles, and relatively better emissions by older diesels as compared to older gasoline vehicles.

BACKGROUND AND OVERVIEW

In much of the world, diesel-powered vehicle sales rose dramatically following the oil price shocks of 1973-74 and 1979. Long the powerplant of choice for most heavy-duty applications, diesels began to make major inroads into passenger car and light truck markets, particularly where tax policies favored diesel fuel (associated with non-discretionary, commercial activity) over gasoline (associated with discretionary personal travel). By 1989 diesels had captured over 10% of the automotive market in West Germany, Spain and Italy where fuel taxes moderately favored diesels and nearly 30% of the French market where the tax structure was even more favorable toward diesels. (Automotive Industry Data Limited, 1995) In the U.S., tax policies went the other way. Diesel taxes rose toward parity (on a Btu basis) with gasoline, and the diesel share of the automotive market plummeted from approximately 6% in 1981 to near zero by 1988. (American Automobile Manufacturers Association, various years) Thus, with the exception of the heaviest light trucks (i.e., primarily those above 8,500 lbs. GVW), diesels have been conspicuously absent from the U.S. light-duty vehicle market. (See Figure 1.)

The U.S. heavy-duty market has long been dominated by diesels. As shown in Figure 2, diesels account for nearly all Class 8 sales, over 70% of Class 7, and approximately 60% of Class 6 truck sales. (American Automobile Manufacturers Association, various years) Although diesels are capturing increasing shares of the lighter truck classes, there is considerable room for growth in these markets. To illustrate, diesels now account for over 70% of the sales of commercial trucks under four tonnes (roughly equivalent to Classes 1 and 2a) in France vs. less than 6% in the U.S. (American Automobile Manufacturers Association, various years. Assumes 50% of all Class 1-2 sales are commercial and all diesels are commercial.)

Indirect injection (IDI) diesels typically get 15-20% better fuel economy and (adjusting for the higher Btu content of the fuel) 6-8% better fuel efficiency than comparable gasoline vehicles. Thus, increased dieselization has been proposed as an energy conservation strategy first in heavy-duty vehicles then, once relatively higher emissions of NO_x, SO_x and particulates (PM10) are resolved, in light-duty vehicles. This two-phased strategy is quite feasible. Diesels have become the standard powerplant for the heaviest vehicles and are becoming increasingly common in the middle ranges. Product development is producing continued advancements in direct-injection (DI) and fuel injection technologies which are bringing the performance and emissions requirements for light-duty vehicles within reach. Moreover, the U.S. Department of Energy’s Office of Transportation Technologies (OTT) is supporting R&D on low-emission diesels for heavy-duty truck applications as part of its Heavy Vehicles R&D program, and advanced light-duty diesels are being considered as both stand-alone powerplants and components of hybrid-electric vehicles as part of the joint government-industry Partnership for a New Generation of Vehicles (PNGV).

Manufacturers both here and abroad have major programs to develop direct-injection diesel engines. Volkswagen and Ford-Europe have begun to introduce vehicles incorporating direct-injection technology. Fuel efficiency improvements on the order of 12-15% over IDI diesels have been demonstrated in production vehicles and another 12-15% may be possible in more advanced engines currently under development.

R&D is clearly moving quickly. Planning and policy analysis are striving to match that pace, to answer such questions as "Is diesel the way to go?" before events overtake the decision process and policy becomes a *fait accompli*. As part of its strategic planning, OTT and its internal program offices have begun to reassess anticipated impacts of OTT-supported research and reevaluate their program portfolio. Individual program offices are developing strategic plans which are being integrated to produce OTT strategic and long-range plans. It is against this backdrop that this analysis was conducted.

METHODOLOGY

Although OTT has long supported research on advanced, heavy-duty diesel engines, and has begun to support work on light-duty diesels, there has been no coordinated diesel strategy as such. Thus, a key feature of this analysis is the consideration of diesels in all classes of highway vehicles. As a practical matter, however, the analysis focused primarily on autos, light trucks and Class 8 trucks (those above 33,000 lbs. GVW) because these are the major energy-consuming vehicle classes. Of these vehicle classes only Class 8 trucks currently account for a significant portion of diesel fuel use. The scope was retrospective rather than prospective — that is, historical data were used to develop estimates for 1992, the reference year for the analysis. Increased penetration of diesels into auto and light truck stocks was simulated using hypothetical market penetration rates. The Integrated Market Penetration and Anticipated Cost of Transportation Technologies (IMPACTT) model which incorporates a survival function based on earlier work by Greene and Rathi was used to estimate light-duty vehicle stocks, fuel savings, and emission reductions. (Mintz, 1994; Greene and Rathi, 1990) Necessary inputs were obtained from EPA's MOBILE5A model and ANL's GREET model. (Wang, 1996) Diesel penetration into medium and heavy truck classes was simulated by adjusting vehicle stock distributions as reported in the 1992 Truck Inventory and Use Survey (TIUS). (U.S. Department of Commerce, 1993)

Any number of hypothetical scenarios, from a bit more than actual U.S. market penetration to 100% dieselization, could be used to estimate the impact of increased dieselization. Clearly, small increases will result in small impacts which may be difficult to measure and of little consequence. Although more interesting from an analytical perspective, larger increases may be unrealistic. A realistic, mid-range scenario lies somewhere between these two extremes. Because France has the highest dieselization of any developed country, French diesel sales shares by market segment for the period 1970-1990 were used to construct a mid-range scenario. Figure 3 illustrates idealized or smoothed market penetration rates for light-duty vehicles as calculated from French diesel sales shares, while Figure 4 provides additional detail on the market assumptions behind the diesel scenario.

RESULTS

Using the above-described scenario of diesel market penetration and historical U.S. survival functions, vehicle stocks, fuel use and emissions were estimated for 1992 and compared with those for a non-diesel, or base case, for that year. The latter was developed from actual diesel sales of new light-duty vehicles; national estimates of vehicle stocks, VMT and fuel use; and estimated emission rates by calendar year, vehicle model year and fuel type. Figures 5-8 show the results. Figures 5 and 6 contrast 1992 gasoline and diesel shares of vehicle-miles traveled (VMT) by market segment under the base verses the diesel scenario, while Figure 7 shows fuel use and petroleum savings for the diesel case. As shown in Figure 7, after 22 years of increased dieselization, the diesel case resulted in a 0.5Q (0.245 MMBD) reduction in 1992 petroleum use. Approximately 52% of this reduction came from automobiles while most of the remaining 48% came from light-duty trucks.

Figure 8 illustrates the difference in 1992 emissions under the diesel case. Both tailpipe and upstream emissions changes for NO_x, HC, CO, $S0_x$, PM10, and CO_2 are shown. Tailpipe emission rates by vehicle and fuel type (auto and light truck, gasoline and diesel) were obtained from EPA's MOBILE5A model and used to estimate downstream emissions by the surviving stock of vehicles in each calendar year. Upstream emission rates for gasoline and diesel fuel were obtained from the GREET model. (Wang, 1996) The largest reduction (45.7 million tonnes) occurred in CO_2 emissions (26.8 million downstream and 18.9 million upstream). CO emissions declined by 6.3 million tonnes while HC emissions dropped by a bit less than 0.8 million tonnes. NO_x emissions also dropped slightly, while SO_x and PM10 increased. With the exception of NO_x, all emissions changes were in the expected range and direction. The unexpected NO_x findings were subjected to closer scrutiny. Upon closer examination, NO_x declines were found to arise from marked variations in the emissions profiles of gasoline as compared to diesel vehicles. Declines in the emissions rates of new gasoline vehicles (in response to tighter standards over the 1970-1992 timeframe) were more than offset by increases in emissions of all criteria pollutants as gasoline vehicles aged. Specifically, one-year old gasoline cars emitted NO_X at a rate of 4.126 g/mi in 1971, 0.77 g/mi in 1981, and 0.58 g/mi in 1991. By 1991, however, 11-year old cars (the one-year old vehicles in 1981) emitted NO_x at a rate of 2.503 g/mi (225% more than when a year old). By contrast, one-year old diesel cars emitted 1.469 g/mi NO_x in 1971, vs. 1.317 g/mi in 1981 and 0.877 g/mi in 1991, and 11-year old diesel cars emitted 1.249 g/mi in 1991. Thus, diesel vehicles had no degradation over time despite significantly less improvement in response to new emissions standards. Moreover, in many cases, the NO_x emission rate of older diesel vehicles is less than that of same-vintage gasoline vehicles.

The refinery impact of dieselization has been considered before. In earlier studies (McNutt, 1981; Schneider, 1981), refinery energy consumption for distillate production was taken to be approximately equivalent on a volumetric basis to the energy required to produce gasoline. A more recent study (Waters, 1992) concludes the same, but cites several other studies from 1981.

Since the early 1980s, interest in dieselization has cooled considerably. The National Petroleum Council (NPC) analyzed diesel fuel in its 1993 report *U.S. Petroleum Refining: Meeting Requirements for Cleaner Fuels and Refineries*, though the primary motivation was the implementation of an ultra-low sulfur specification (0.05% wt) for on-highway diesel fuel under the Clean Air Act Amendments of 1990 (CAAA) rather than any consideration of increased diesel fuel use.

Though the assumption of volumetric equivalence between diesel fuel and gasoline for refinery energy consumption may have held true in 1981 — essentially, the greater energy density of diesel fuel being offset by the lower refinery energy processing requirements — it probably does not hold for a U.S. refinery as currently configured. Rather, on a volumetric basis, diesel consumes more energy than gasoline, while on an energy basis somewhat less energy is consumed at the margin (personal communication with B. McNutt and R. Warden). De-bottlenecking, equipment upgrades and refinery fuel switching, and refinery closures have all contributed to increased refinery process efficiency over the last decade or so (NPC, 1992).

The imposition of low-sulfur standards (and aromatic content limits) on diesel fuel has been primarily responsible for the decrease in process efficiency of diesel fuel relative to gasoline. Hydrotreating heavier fractions of petroleum requires higher temperature and pressure than lighter fractions. Indeed, gasoline blendstock processing tends to reduce sulfur incidentally to the product's specifications. (McKetta, 1992)

For purposes of this study, it was desirable to estimate the effect of dieselization over the 1970 to 1992 period. The solid line in Figure 9 shows an estimate of refining energy saved over the period of study assuming volumetric equivalence for gasoline and diesel fuel process energy. The dotted line incorporates a penalty for diesel desulfurization and associated process inefficiencies (e.g., requirement for additional hydrogen plants to supplement hydrogen supply from the catalytic reformer).

There is an additional factor which reduces the efficacy of a dieselization strategy specifically for crude oil displacement. Due a combination of legally mandated oxygen content (e.g., in reformulated gasoline), the phase-out of lead-based additives, and the reduction of aromatics which formerly provided octane in gasoline, the U.S. gasoline pool today contains a substantial volume of non-petroleum derived fuel components. Additionally, as the product balance between gasoline and diesel changes beyond current seasonal variations, it may be necessary to utilize more extreme processing which could be both expensive in capital terms and energy-inefficient (e.g., heavy-oil cracking). Finally, as available crude oil becomes heavier, processing energy efficiency will likely decline (unless offset by technological improvements).

The margin, however, does not represent well a fuel switch of the magnitude considered in this study. A number of processing changes can be envisioned which would marginally increase the ratio of diesel fuel to gasoline (D/G ratio). For example, considerably more hydrodesulfurization could be required. This could stress an already tight hydrogen supply. As one increases the D/G ratio further, however, the processes which must be employed become more extreme. In some cases, the necessary processing would be both speculative (i.e., so heterodox as to be untested) and extremely expensive. It is conceivable, for example, that the ratio of diesel fuel to gasoline could be increased by polymerizing small olefins, but this is likely to be a rather expensive route to producing diesel fuel. If such strategies are assumed, it might be reasonable to assume the use of a Fischer-Tropsch synthesis from natural gas as an economic alternative. Determining the capital and operating expenses which limit the D/G ratio is a more complicated problem than speculating that it is probably not economical to use a shift to diesel fuel as a refining energy conservation measure. The vast majority of the potential gains would come from improved fuel economy due to the superior thermal efficiency of the engine rather than from refining process energy.

Hydrogen availability is difficult to assess as a material balance. In economic terms, however, demand for hydrogen would likely limit the rate at which a dieselization strategy could be deployed. Hydrogen supplies in the refinery would be reduced due to less utilization of the catalytic reformer (because of aromatic controls). At the same time, it could be assumed that lower utilization rates for hydrocracking would reduce demand. However, the ultra-low sulfur requirement for diesel fuel (and additional diesel fuel produced) implies that a great deal of hydrotreating capacity would be required, which represents more demand.

The NPC estimated that making all on-highway diesel compliant with ultra-low sulfur requirements would cost 2.4 billion dollars (1990 dollars) in capital investment (NPC, 1993). The NPC based its distillate cases on a no-growth demand scenario for 1995, so it is reasonable to assume that the cost figure is too low for a high diesel case such as that considered in this study. The NPC investment figure is based on an on-highway diesel fuel volume of 1366 MB/D and represents a mix of upgrading existing distillate desulfurization units (1300 MB/D) and the addition of new units (250 MB/D). As currently configured, from 500 to 600 MB/D additional middle distillate can be produced by U.S. refineries (NPC, 1993). Such production comes primarily at the expense of gasoline and can be sustained, though not indefinitely.

Another potentially limiting economic constraint for dieselization is that, once necessary capital investment is included, U.S. refineries may not be the low-cost marginal producer of distillate. This would tend to increase the fraction of imported finished fuels relative to the base case. This could accelerate the rationalization of the U.S. refining industry and increase vulnerability to supply disruptions and sensitivity to oil price shocks. It is worth noting that the NPC did not predict an increase in light-product (gasoline, jet fuel, and diesel) imports as a result of U.S. fuel modifications such as the adoption of RFG and ultra-low sulfur diesel. This is in spite of the fact that the primary economic burdens imposed on the refining industry were determined to be facility regulations rather than product quality changes.

The U.S. refining industry is now typically maximized for gasoline production rather than for diesel fuel production. Recent cold snaps (e.g., December, 1991; December, 1995) and the Gulf War have resulted in temporary increases in middle distillate production which demonstrate the flexibility of the refining (and logistics) systems. This short-term flexibility, however, is not representative of the scale which the changes envisioned would require.

CONCLUSIONS

Though significant, the 0.5 quad reduction in 1992 fuel use estimated for a moderate diesel scenario amounts to only 3.7% of the energy consumed by light-duty vehicles in that year. This modest energy saving suggests the following conclusions:

1. Technological substitution takes time. Even after 22 years of increased diesel penetration, savings are well below 5%. Because of the slope of the market penetration curve, a longer timeframe is needed to capture the full effect of this scenario.

2. Diesel cannot substitute for gasoline on a one-for-one basis. Gasoline contains a significant fraction of oxygenates and other additives derived from non-petroleum sources. Diesel currently has very little non-petroleum content (although things could certainly change with increased use and closer scrutiny of diesel emissions).

3. Like fuel economy, emissions rates vary by model year, fuel type, and as vehicles age. Because of this complexity, aggregate estimates could well be erroneous. The conventional wisdom predicts NO_x increases from increased dieselization. This was not supported. Note that the PM10 and SO_x emissions (164,000 and 34,000 tonnes, respectively) represent increases of 35-40% over base-level emissions by LDVs. These are the largest impacts of a light-duty diesel strategy. However, because current LDVs are not major sources of PM10 and SO_x emissions, the affect of these increases on total emissions is much less (comprising an increase of 0.4% and 0.2%, respectively, on a national basis).

4. A dieselization strategy may have additional impacts on particulate emissions by increasing/decreasing precursors, most notably NO_x, SO_2 and secondary organic aerosols. While increases in SO_2 may elevate particulate emissions they may be offset by relatively lower emissions of secondary organic aerosols.

5. The significance of refinery energy and oil consumption is reduced for a dieselization strategy by the need for increased hydrodesulfurization. Without this additional requirement, energy savings would probably still be too modest to justify a switch on the grounds of saving energy and oil. Gasoline production, for which U.S. refineries tend to be maximized, is a fairly efficient process. At the margin, increasing diesel output may decrease energy requirements within refineries, but this is unlikely to be the case for changes in average product slate. Energy and petroleum savings due to improved thermal efficiency of vehicle engines is a far more significant source of oil and energy savings.

6. With the exception of truly dramatic technological advancements, most efficiency improvements have a limited scope for petroleum reduction. Dramatic reductions in oil use and imported oil dependence are more likely to come from substitution of non-petroleum fuels than from efficiency improvement and/or substitution of one petroleum fuel for another.

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FIGURES

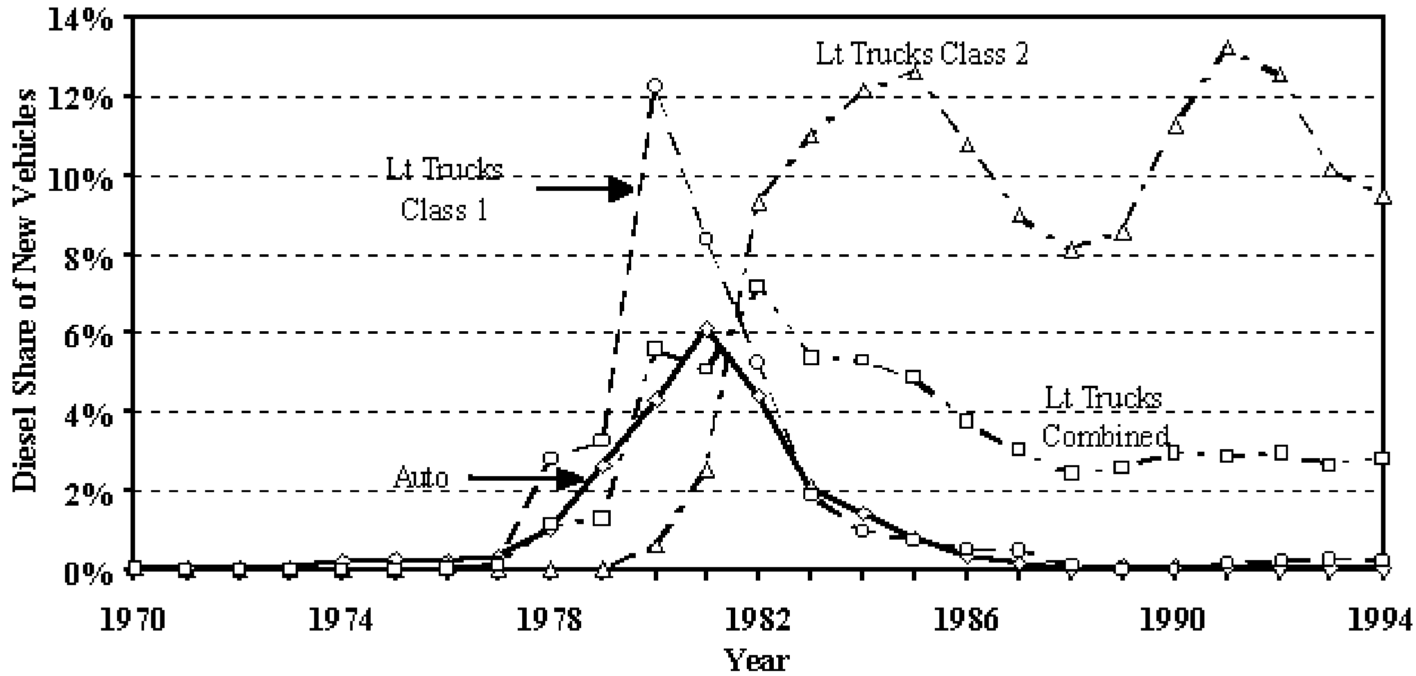

Fig. 1 Historical Diesel Market Penetration in the Light Duty Segment

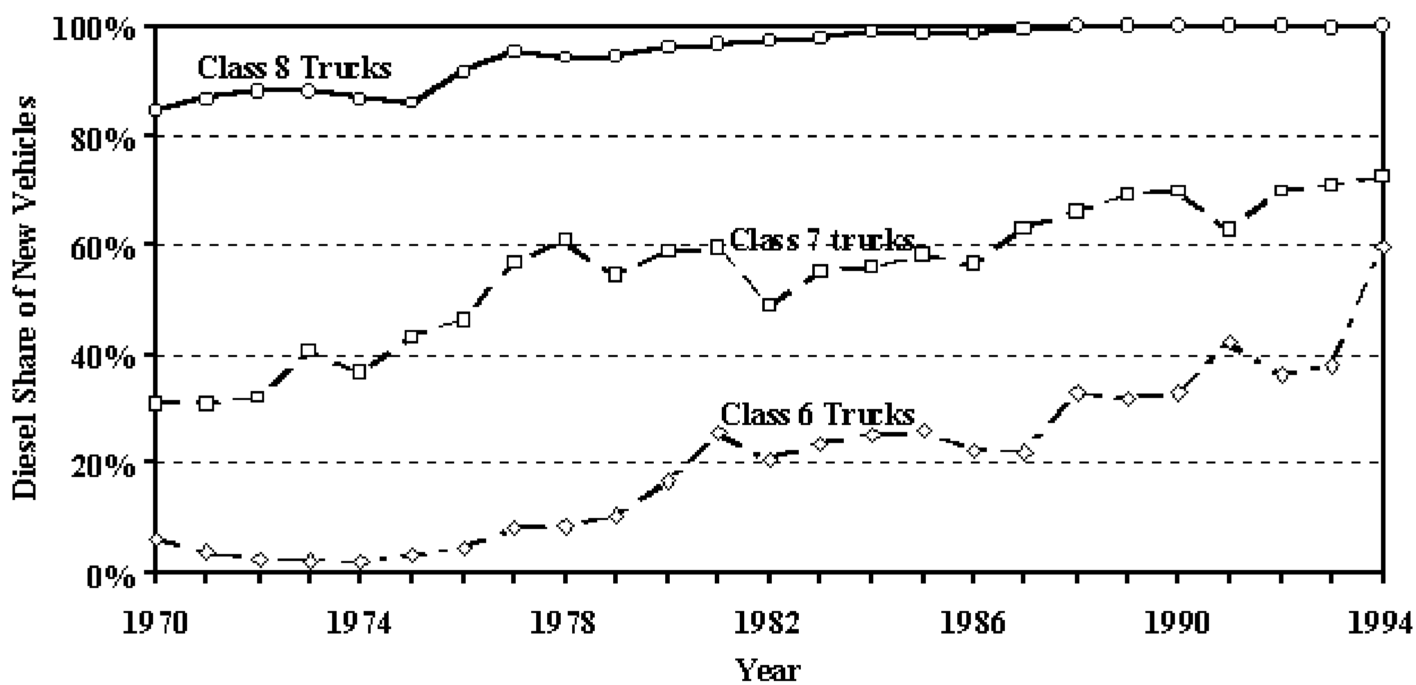

Fig. 2 Historical Diesel Shares in Truck GVW Classes 6-8

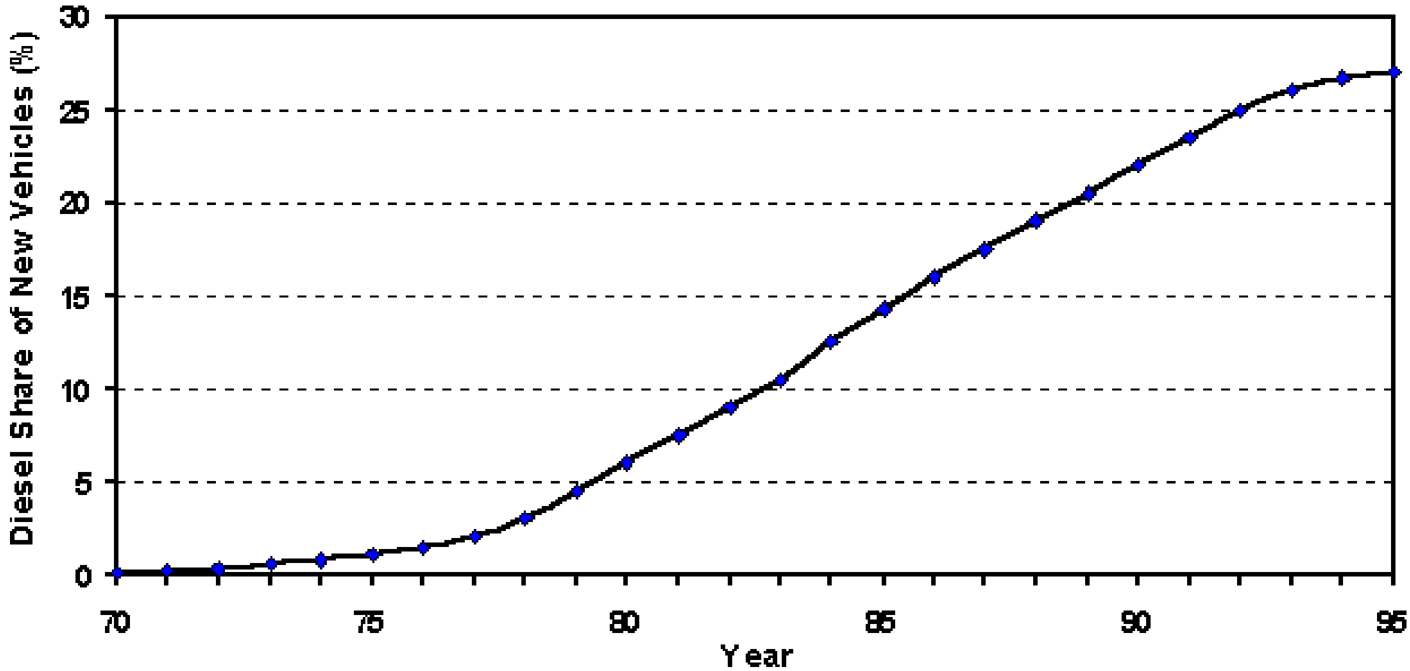

Fig. 3 Light-Duty Market Penetration Profile for the High Diesel Scenario

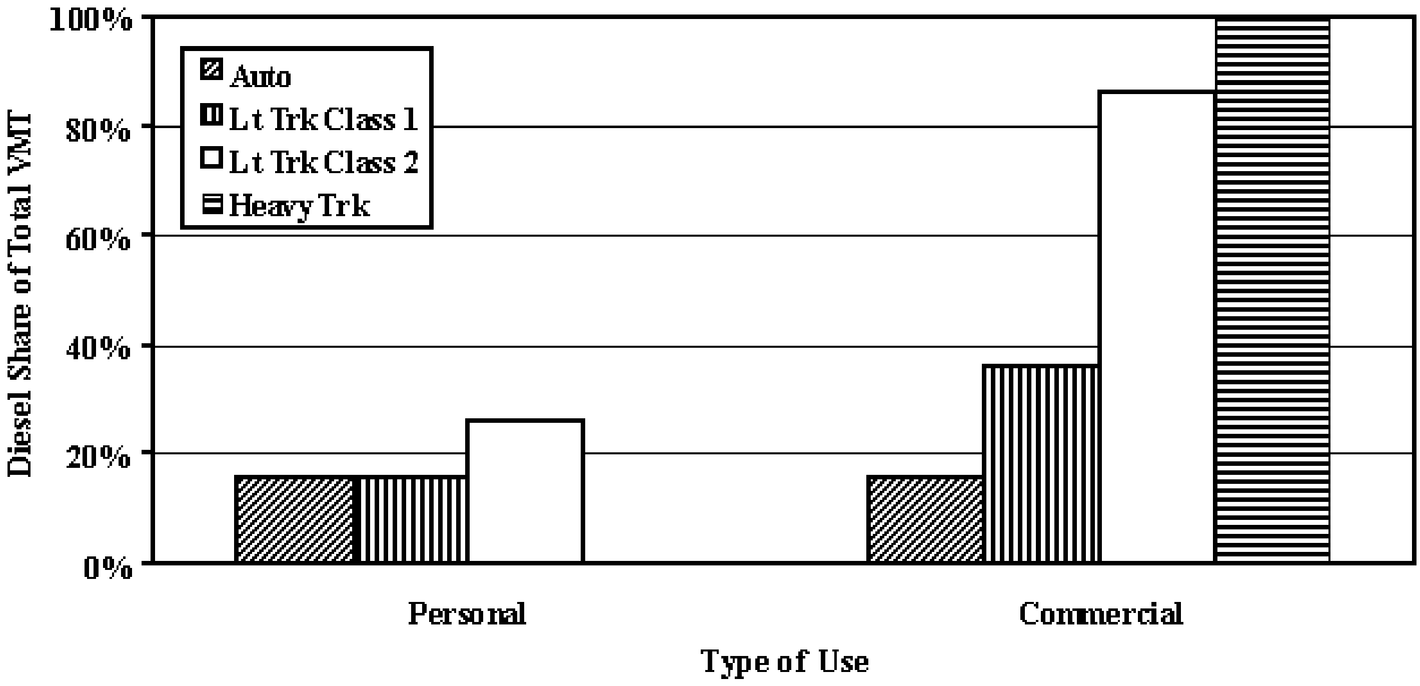

Fig. 4 Diesel Share Assumption for the High Diesel Scenario in 1992

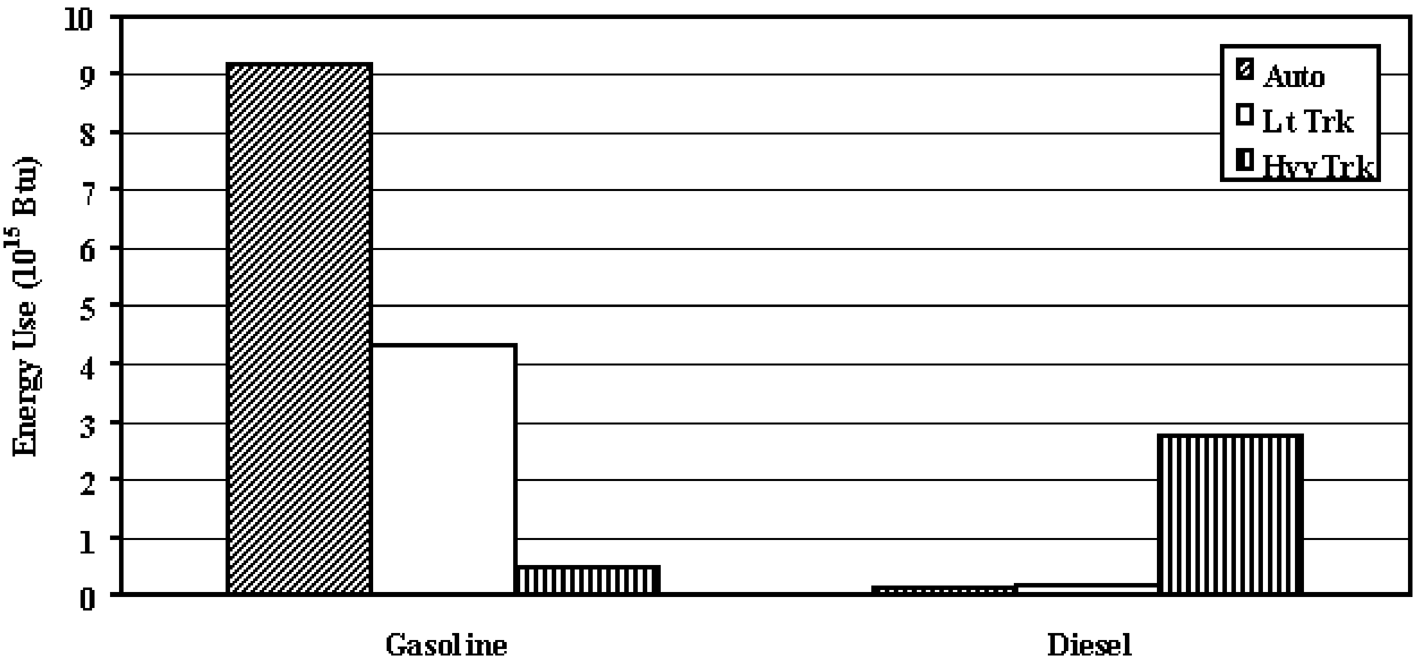

Fig. 5 Highway Vehicles Energy Consumption Under the Base Case

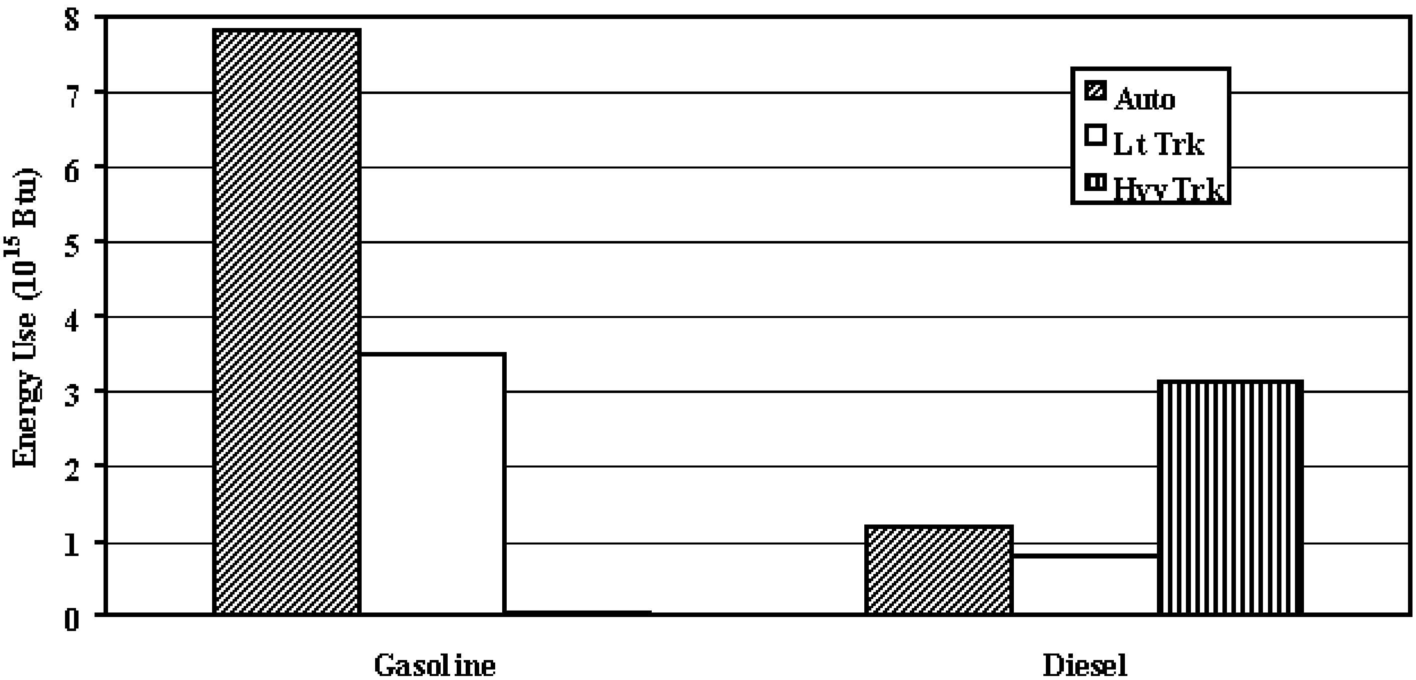

Fig. 6 Highway Vehicle Energy Consumption Under the High Diesel Case

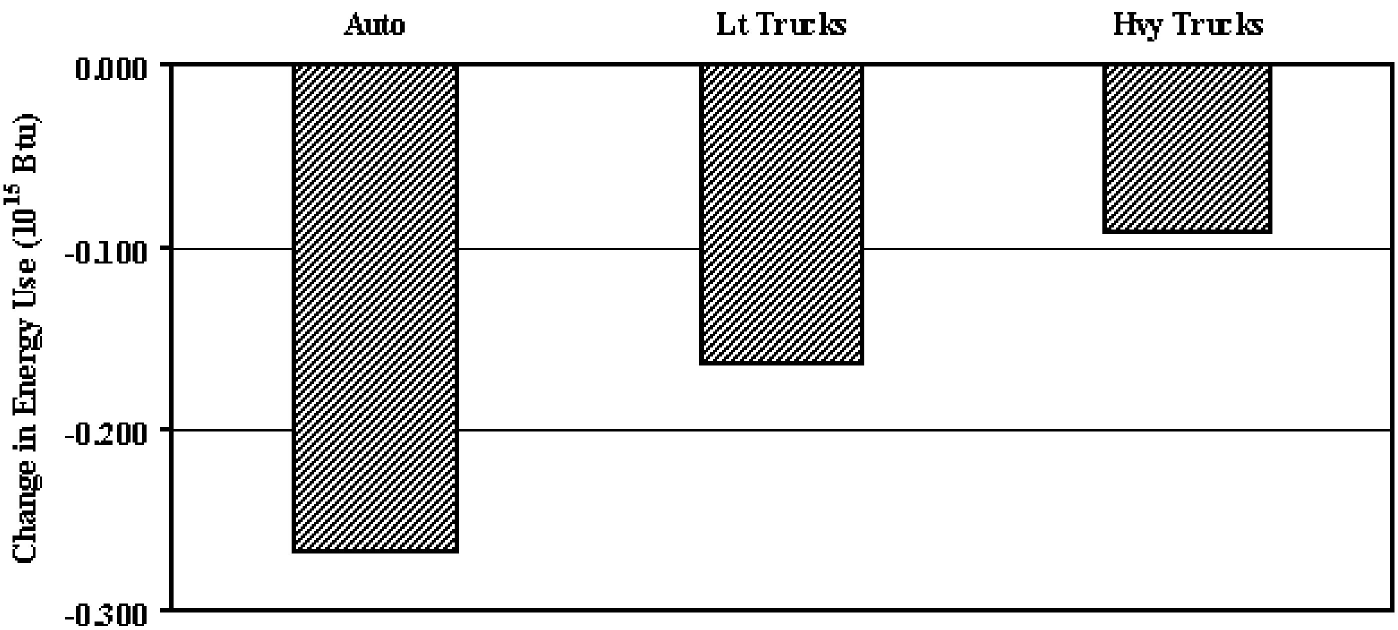

Fig. 7 Change in Energy Consumption by Vehicle Type

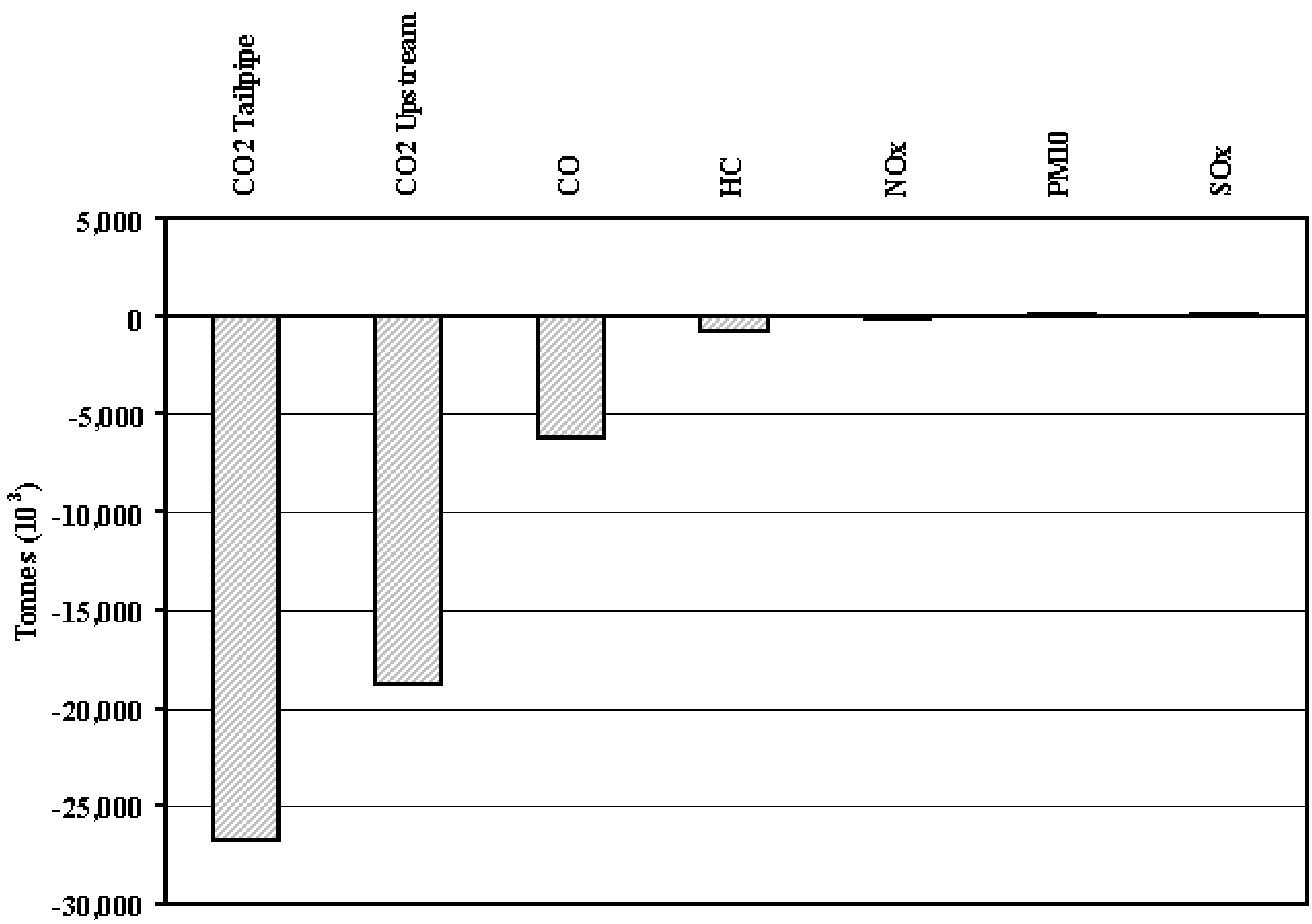

Fig. 8 Change in Criteria Pollutant and CO_2 Emissions

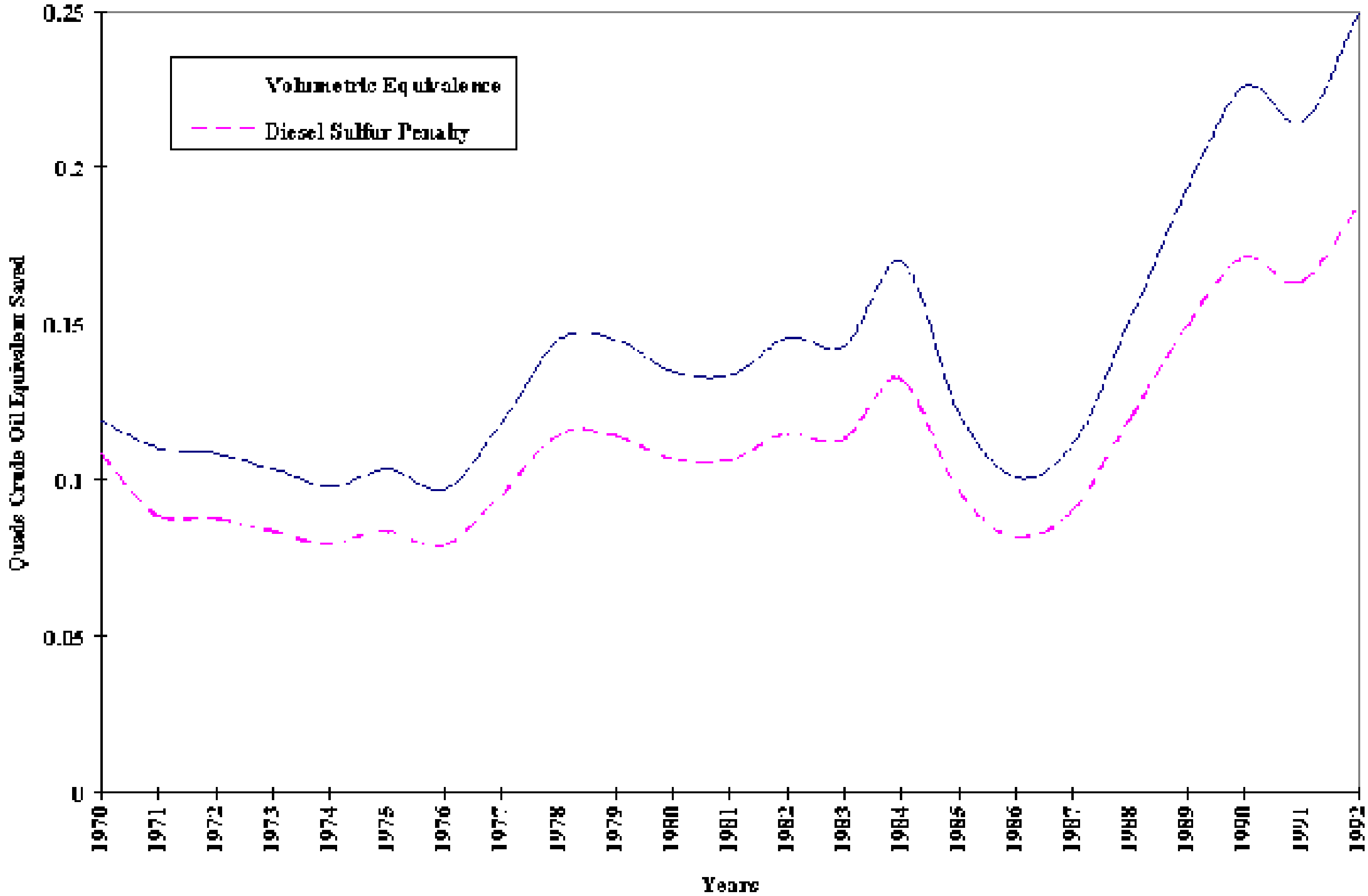

Fig. 9 Estimated Refinery Energy Savings Relative to Base Case